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Guillaume Dubois, Julien Cesbron, Fabienne Anfosso-Lédée, Yin Hai-Ping. Low frequency statistical estimation of rolling noise from numerical tyre/road contact pressures. Acoustics 2012, Apr 2012, Nantes, France. <hal-00810621>

HAL Id: hal-00810621

<https://hal.science/hal-00810621v1>

Submitted on 23 Apr 2012

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ACOUSTICS 2012

Low frequency statistical estimation of rolling noise from numerical tyre/road contact pressures

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The paper deals with the relation between numerical contact data and close-proximity (CPX) noise measurements. The noise was measured on several road surfaces together with the texture in three dimensions on two-meter-long sections. A multi-asperity contact model was used to obtain successively the contact forces distribution and the contact pressure distribution between a patterned standard tyre and the road during rolling. The correlation between third-octave contact force levels and noise levels was studied on a set of ten surfaces. A high positive correlation is found at low frequency below 800 Hz, which allows the estimation of noise levels by means of statistical relations for each third-octave band between 315 Hz and 800 Hz. The results of the model are discussed in relation to the standard deviation of CPX measurements.

1 Introduction

Several mechanisms are responsible for the generation of tyre/road noise. There are two main approaches for modelling tyre/road noise: deterministic models and statistical models. The principle of the deterministic approach is to model the full physical mechanisms from the characteristics of the road and the tyre. In the statistical approach, noise is estimated either by correlations with the characteristics of the road and/or the tyre (empirical models) [1, 2], or by correlations with quantities from physical models (hybrid models) [3, 4, 5, 6]. Below 1000 Hz, tyre/road noise is mainly due to radial tyre vibrations originated by tyre/road contact [7]. Thus hybrid models are mainly based on correlations of noise with results of tyre/road contact models. These previous studies have shown strong relationships between the texture of road surfaces, the contact forces and the measured noise.

In this paper, we introduce a hybrid method and focus on the statistical relationship between calculated contact forces using a physical contact model [8] and measured CPX noise levels [9]. The first part is devoted to the presentation of the road surfaces and the measured noise spectra. The second part relates to the calculation of contact forces spectra. In the last part, the correlation between the calculated contact forces and the measured noise is presented and a hybrid method for the prediction of low frequency noise is discussed before conclusions.

2 Third-octave noise levels

2.1 Road surfaces and texture data

The study is based on different road surfaces of the test track of IFSTTAR (Nantes, France). On the one hand, three dimensional texture measurements of the road surfaces were carried out, to be used as input data in the contact model. On the other hand, close-proximity (CPX) noise was measured on the same surfaces. Ten road surfaces are used in this study. They are denominated by letters in Figure 1, according to the names used on the track. Surface A is a Rough Surface Dressing (Rough SD) 8/10, A' is a Porous Asphalt (PA) 0/6, C is a Fine Surface Dressing (Fine SD) 0.8/1.5, E1 and E2 are Dense Asphalt Concretes (DAC) 0/10 respectively new and old, F is a Colgrip with high skidding resistance (Colgrip) 1.5/3, G is a Flexible Asphalt Concrete (FAC) 0/10, L2 is a Sand Asphalt (SA) 0/4 and M1 and M2 are Very Thin Asphalt Concretes (VTAC) of grading 0/10 and 0/6 respectively. Three dimensional texture measurements of the road surfaces were performed using a stereoscopy method within the framework of the Deufrako P2RN project [10]. The measured surfaces have a spatial resolution $h_x = h_y = 0.384$ mm in the (x, y) plane and a vertical resolution $h_z = 0.038$ mm.

The dimensions of the surface are about $L_x = 2.3$ m in the rolling direction and $L_y = 0.36$ m in the transverse direction.

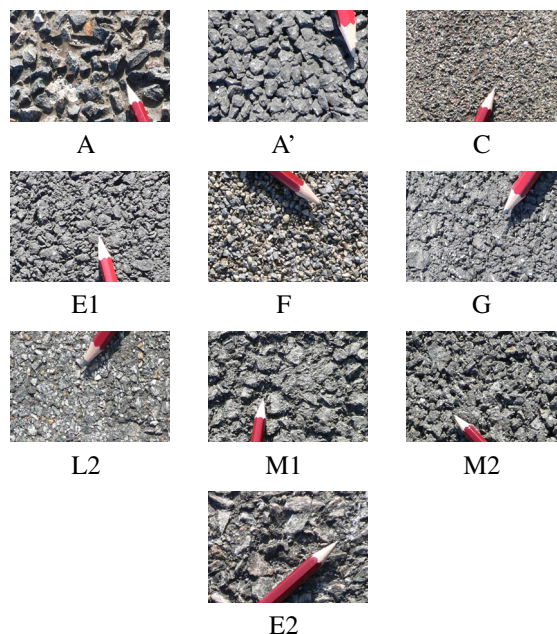


Figure 1: Upper view of the ten road surfaces used.

2.2 Tyre/road noise measurement

Tyre/road noise was measured using a CPX equipment developed at IFSTTAR [9] (Figure 2). The test vehicle is a Renault Scénic 2.0 liters, fitted with four standard tyres (Michelin Energy E3A, 195/60R/15). Three microphones are mounted close to the rear right tyre, i.e. two lateral microphones (1) and (2) according to [11] and one on the back (3), not used in this study. Sound pressure levels and vehicle speed are evaluated every wheel rotation, i.e. approximately every 2 meters over the length of the road section.

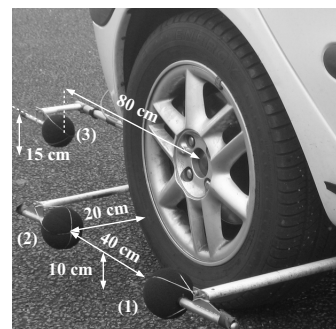


Figure 2: Close proximity noise measurement system.

However, along the test section (≈ 200 m depending on surface) the measured speed V and noise level at each third octave $L_N(f_{io})$ vary by more or less 1 km/h and 2 dB respectively. Noise measurements were performed at different speeds, from 65 to 110 km/h every 5 km/h. For each third octave between 315 and 5000 Hz, a linear regression between the measured noise level and the base-10 logarithm of the speed V (divided by a reference velocity V_{ref}) is calculated. An example is given in Figure 3 for $V_{ref} = 90$ km/h.

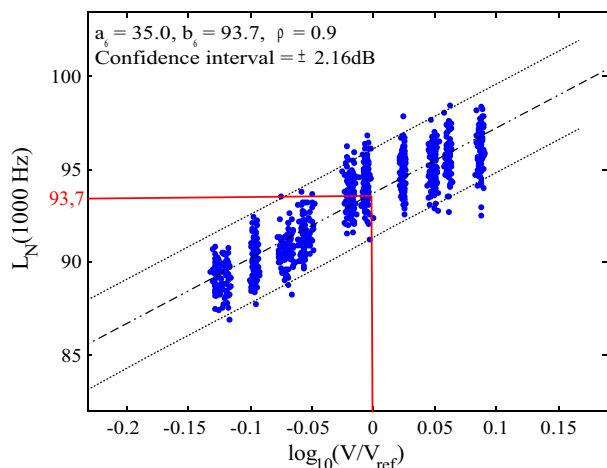


Figure 3: Example of linear regression between the noise level at 1000 Hz and the speed V ($V_{ref} = 90$ km/h, DAC 0/10 surface (E2)).

From the linear regression $L_N[f_{io}] = a_i \log_{10}(V/V_{ref}) + b_i$ with $f_{io} \in [315 - 5000]$ Hz, the calculation of noise levels for each third-octave band is possible at the desired speed (here 90 km/h). The standard deviations σ_i of the linear regressions are needed for a weighted correlation of noise with the output data of the contact model. The values of coefficients a_i vary between 20 and 40. They are relatively close to 30, which is a common value for the overall A-weighted level in the literature.

2.3 Third-octave noise level spectra

The noise level spectra in third octave bands, recomposed from the linear regression analysis, are given in Figure 4 at 90 km/h for all surfaces. The normal contact forces mainly affect the noise at low frequencies by vibration and impact mechanisms. Therefore all the spectra in this paper include a delineation at 1000 Hz.

The noise spectra tested allow to differentiate the acoustic properties of the surfaces. At low frequency (315 to 1000 Hz), knowing that there is a positive correlation between noise levels and macro-texture levels, the noise is directly influenced by the grading. Above 1000 Hz, absorption properties and reduction of air-pumping phenomenon are predominant. A peak is observed at 1000 Hz for all surfaces but surface A. This peak depends on complex mechanisms [7].

3 Third-octave contact force levels

3.1 Contact forces on several meters of road

To study the relationship between noise (Figure 4) and contact forces spectra, it is necessary to define an average spectrum of contact forces in the contact patch during rolling

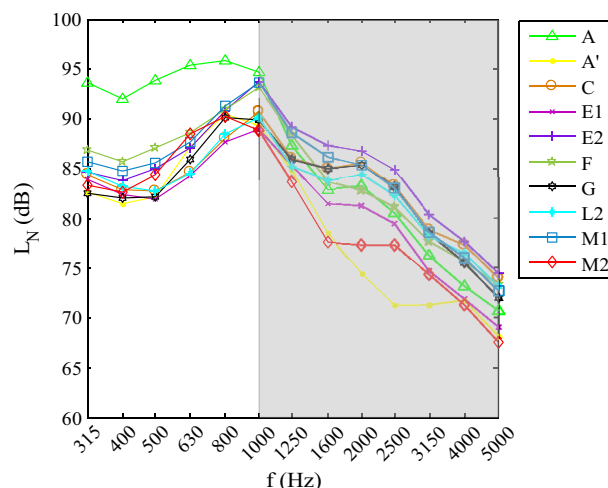


Figure 4: Recomposed third octave bands noise levels at 90 km/h for each surface.

at speed V . The method used to obtain dynamical contact forces on several meters of texture consists in a serial of static states in the rolling direction (with $L_x \approx 2.3$ m) of the Two-scale Iterative Method (TIM) [8]. There are two steps in the calculation procedure:

- Step 1: after loading the tyre on the surface, the calculations are performed at the macro-scale (contact forces distribution);
- Step 2: calculations are performed at the micro-scale (pressure distribution).

It was found necessary to perform both calculation steps to avoid some issues encountered when only step 1 is performed (generation of a low-pass filter, over or under-estimation of contact forces) [12]. The method is illustrated Figure 5 in the frame $\mathcal{R}_O(O, X, Y, Z)$.

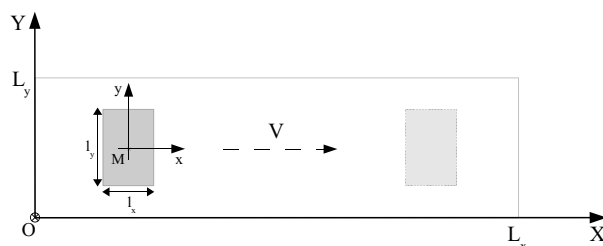


Figure 5: Schematic view of the contact calculations on several meters of road surfaces.

Between two time steps, a rectangular area of interest linked to the frame $\mathcal{R}_M(M, x, y, z = Z)$ is moved at the speed 90 km/h. The size of this rectangular area ($l_x \times l_y$) is $l_x \approx 14$ cm and $l_y \approx 23$ cm. The point $M(X_M, Y_M)$ is the center of the area of interest. In order to obtain a single spectrum of contact forces representative of the surface texture, three calculations of dynamical contact forces are made for three different positions along Y :

$$M \in \{M_1; M_2; M_3\} \quad (1)$$

with :

$$X_{M_1} = X_{M_2} = X_{M_3} \in \left[\frac{l_x}{2}, \frac{l_x}{2} + h_x, \dots, L_x - \frac{l_x}{2} \right] \quad (2)$$

$$Y_{M_1} = \frac{L_y}{2}; Y_{M_2} = L_y - \frac{l_y}{2}; Y_{M_3} = \frac{l_y}{2} \quad (3)$$

To insure the convergence of the TIM at the macro-scale, the area of interest is moved from $h_x = 0.384$ mm at each time step, which corresponds to the mesh resolution of the road and the tyre surfaces. The procedure starts with a loading phase at a fix position until the total load $P = 3000$ N is reached. This corresponds to a typical tyre/road loading for passenger cars. Then, the rolling calculation is performed keeping $P = 3000$ N at each instant.

At the micro-scale, the time step is chosen to obtain a correct sampling frequency ($f_s > 10000$ Hz) in a reasonable time, i.e. we compute only the first iteration of the TIM at micro-scale called the iteration zero and:

$$f_s = \frac{V}{6h_x} \quad \text{and} \quad dt = \frac{1}{f_s} \quad (4)$$

The time vector is then defined by:

$$t \in [0, dt, 2dt, \dots, t_{max}] \quad \text{and} \quad t_{max} = \frac{L_x - l_x}{V} \quad (5)$$

The tyre is represented by an elastic half-space with a Young's modulus of 2.5 MPa and a Poisson's coefficient of 0.5. During the Deufrako P2RN project [10], the three dimensional surface of a non-deformed standard tyre has been measured by optical sensor ($dx = 0.4717$ mm, $dy = 1$ mm). The surface of the tyre is generated for every time step with the same spatial resolution than the mesh of the road ($dx = dy = h_x = h_y = 0.384$ mm), knowing the radius of the tyre ($R = 292$ mm). An example of the tyre surface potentially in contact with the road is given in Figure 6.

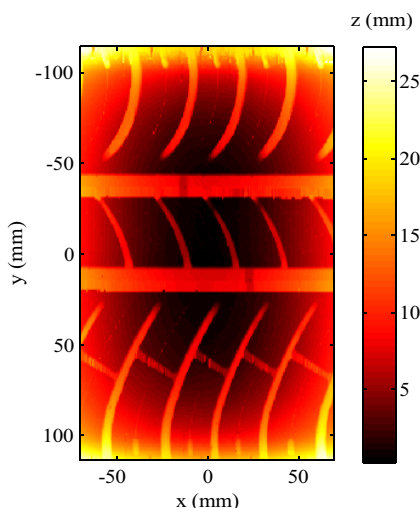


Figure 6: Standard tyre surface potentially in contact with the road for a given time step.

3.2 Contact forces spectra

After calculation of the pressure distribution at the three positions M , the contact forces spectrum in third-octave band for a given texture is defined by the average of the spectra at the three positions:

$$L_F(f_{io}) = \left\langle 20 \log \left(\frac{S_{F^r}(f_{io})}{F_{ref}} \right) \right\rangle, \quad r \in \{1; 2; 3\} \quad (6)$$

where the reference contact force F_{ref} is equal to 1.10^{-7} N and the contact force spectrum for one run $S_{F^r}(f_{io})$ is defined in the frame \mathcal{R}_M by:

$$S_{F^r}(f_{io}) = \frac{1}{\Delta y} \int_{-\frac{\Delta y}{2}}^{\frac{\Delta y}{2}} S_{F^r}(y, f_{io}) dy \quad (7)$$

where $\Delta y = (2q_y + 1)h_y$, with for the present study: $q_y = 225$. To take into account what has happened in the whole contact area, the contact force spectrum $S_{F^r}(f_{io})$ is the average in the transverse direction of every spectra (in third-octave band) in the middle of the contact area. Each spectrum is then the Fourier transform of the autocorrelation function, calculated from each windowed (Hanning) signal $F^r(y, t)$:

$$\forall t \in [0, t_{max}], \quad \forall y \in \left[-\frac{l_y}{2} + \frac{h_y}{2}; \frac{l_y}{2} - \frac{h_y}{2} \right],$$

$$F^r(y, t) = \int_{y-\frac{dx}{2}}^{y+\frac{dx}{2}} \int_{-\frac{dx}{2}}^{\frac{dx}{2}} p^r(\xi, \eta, t) d\xi d\eta, \quad (8)$$

Finally, the spectra of the contact forces in third octave bands at 90 km/h for the ten road surfaces are illustrated in Figure 7.

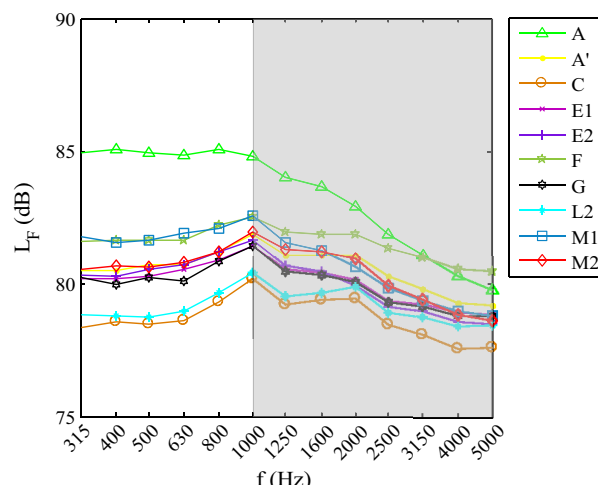


Figure 7: Calculated third-octave contact forces spectra at 90 km/h for the ten road surfaces.

At low frequency, the classification of surfaces relative to contact forces is similar to that observed with noise levels (Figure 4), and is mainly related to the grading and the density of asperities of the road surface. At high-frequency, this classification of surfaces is different from the one with noise, as the effects of sound absorption and air-pumping is not integrated in the force spectra. A significant peak is observed at 1000 Hz in Figure 7 for all surfaces but surface A at 90 km/h. This peak is probably related to the quasi periodicity of the tread blocks of the tyre and to the speed by the following equation:

$$f_{peak} = \frac{V}{l_{tread\ block}} \quad (9)$$

For $V = 90$ km/h with an average width of tread block $l_{tread\ block} \approx 25$ mm (cf. Figure 6), the frequency of the peak is equal to 1000 Hz, as observed in Figure 7.

4 Low frequency statistical estimation of rolling noise

4.1 Statistical correlation between calculated contact forces and measured noise

Figures 8 and 9 show the statistical correlation between calculated contact forces and measured noise spectra. Iso-correlation curves at 90 km/h are shown in Figure 8. A strong

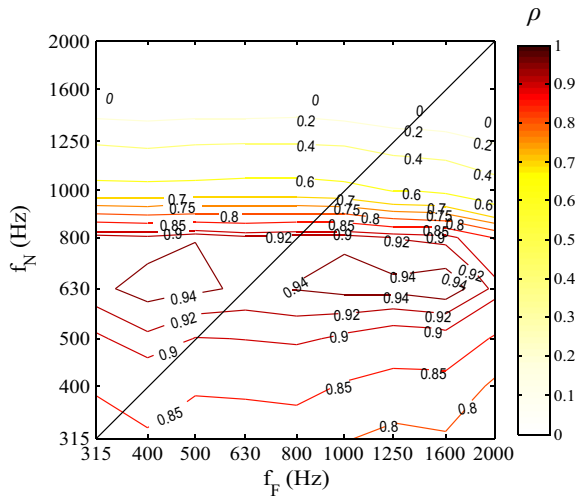


Figure 8: Force/noise iso-correlation curves at 90 km/h.

correlation ($\rho \geq 0.8$) is observed between noise levels from 315 to 800 Hz and force levels from 315 to 2000 Hz. Above 1000 Hz for noise, the correlation coefficient drops sharply. The results on the first bisector ($y = x$) are shown in Figure 9.

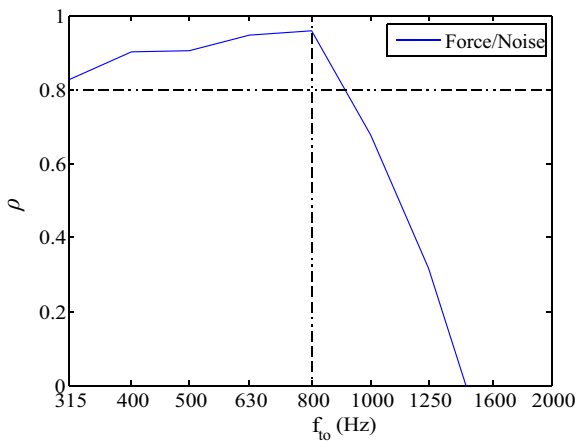


Figure 9: Correlation coefficient at 90 km/h between calculated contact forces and measured noise.

By setting a threshold at 0.8, we can define a cut-off frequency of strong correlation at a frequency of 800 Hz. In conclusion, contact forces and noise are positively correlated in the frequency range 315-800 Hz. Above this threshold of 800 Hz, the correlation is not strong enough to build an estimate of the noise.

4.2 Estimation of rolling noise from numerical tyre/road contact pressures

The correlations presented above allow us to use a hybrid method to estimate noise. In practice, for each third-octave

below the cut-off frequency of high correlation and for each surface, it is possible to obtain the linear regression $L_N(f_{io}) = a_j L_F(f_{io}) + b_j$ with its standard deviation σ_j . To evaluate the relevance of the estimation of third-octave noise levels by this hybrid model, a comparison is made between estimated and measured noise spectra from 315 to 800 Hz for the ten surfaces (5 bands \times 10 surfaces), as represented in Figure 10.

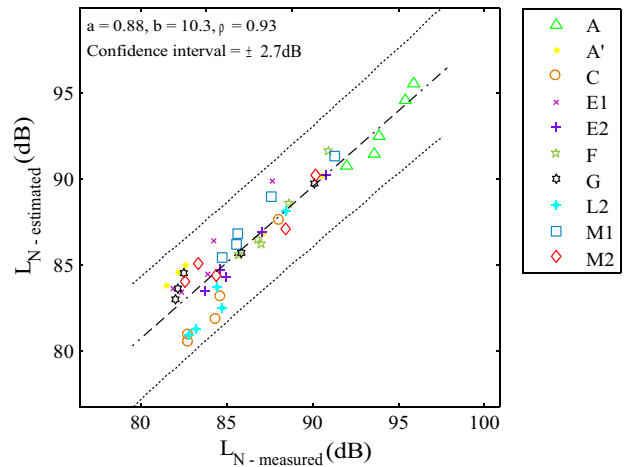


Figure 10: Correlation between measured noise and estimated noise from contact forces by hybrid method.

As expected, a good correlation (0.93) between the two noise levels is obtained. The slope a is close to 0.9 (≈ 0.88) and the offset b is equal to 10.3. Ideally, a slope of 1 and an offset of 0 would be expected, which shows some inaccuracy in the model. The confidence interval ci is equal to ± 2.7 dB, i.e. the standard deviation is equal to $\sigma = \frac{ci}{t_{0.975}^k} = \pm 1.1$ dB (with t_{γ}^k the value of the t-student distribution).

4.3 Comparison with another approach

A comparison of the above-mentioned approach with a simpler statistical model of rolling noise estimation from texture profiles is performed. The texture spectra, illustrated in Figure 11, are obtained from the same method as in section 3.2 using the texture profiles z instead of the contact forces F .

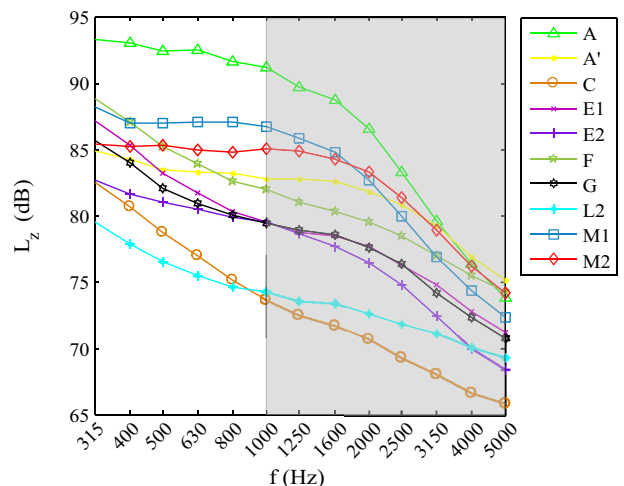


Figure 11: Calculated third octave texture levels at 90 km/h for each surface.

Figure 12 presents the results for the surface E2 of noise level measured, estimated from texture and estimated from contact forces as described in section 4.2. The standard deviations of noise level for each third-octave are indicated by bars.

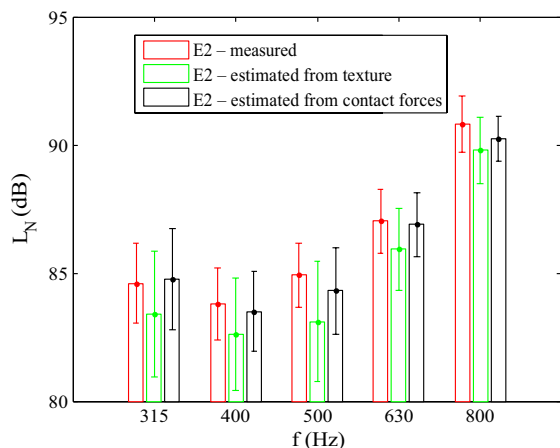


Figure 12: Comparison between measured noise (red), estimated from texture (green) and from contact forces (black).

With both statistical methods, the measured noise is underestimated. However, the estimate from the contact forces is closer to the measurement results than that estimated directly from the texture, either in amplitude, shape of the spectrum and standard deviation for the ten road surfaces.

5 Conclusion

In this study, a low frequency statistical estimation of rolling noise from numerical tyre/road contact pressures has been calculated and compared to the measured rolling noise on ten road surfaces.

The CPX method was used and allowed recomposed noise spectra at a given speed with the standard deviation for each third-octave. The noise level spectra obtained allow to differentiate the acoustic properties of the tested surfaces. At low frequency (315 to 1000 Hz), noise is generated by the tyre vibration, which is influenced by the magnitude of the contact forces at the interface, directly influenced by the grading and the texture. Above 1000 Hz, absorption properties and reduction of air-pumping phenomenon are predominant and not taken into account in this hybrid model.

Then a multi-asperity tyre/road contact model was used to obtain the pressure distribution for a patterned standard tyre rolling on several meters of road surfaces. From this pressure distribution, we obtain contact forces spectra. At low frequency, the classification of surfaces is similar to that observed with noise levels and is mainly related to the grading. A significant peak is observed at 1000 Hz for 90 km/h, probably related to the average width of tread block.

Finally, the correlation between calculated contact forces and measured noise is positively strong until 800 Hz for the ten surfaces used at 90 km/h. By means of a hybrid method, a low frequency statistical estimation of rolling noise has been performed from contact forces and compared to an estimation from texture. The results from contact forces are closer to the measurements, either in amplitude, shape of the spectrum and standard deviation. Nevertheless the results of these

correlations should be confirmed in a future study with more surfaces, using other texture measurements.

Acknowledgments

The authors would like to thank the Deufrako P2RN partners (Bast and Müller-BBM, Germany) for providing 3D road texture data.

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